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Parton Bubble Model Compared with RHIC Central Au+Au $\Delta\varphi$ $\Delta\eta$ Correlations at $\sqrt{s_{NN}} = 200$ GeV

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Abstract

For over two decades we have shared with van Hove the view that if a quark-gluon plasma (QGP) is produced in a heavy ion collider, it is probable that the final state would contain QGP bubbles or droplets (gluonic hot spots), localized in phase space. Earlier we developed a multi-bubble model of localized gluonic hot spots on the surface of the fireball at freeze-out. The bubbles have the approximately 2 fm dimensions of source size observed by HBT work for charged particles with $p_t > 0.8$ GeV/c. We have recently refined our model to become a parton inspired bubble model. In this paper we compare the model predictions with a recent high precision two particle correlation analysis at RHIC. We find we can explain the significant results of this analysis thus providing substantial evidence for the parton bubble model.

1 Introduction

For over two decades we have shared with van Hove the view that if a quark-gluon plasma (QGP) is produced in a heavy ion collider, it is probable that the final state would contain QGP bubbles or droplets (gluonic hot spots), localized in phase space. These hot regions would have a higher multiplicity of particles than the surrounding event[1, 2, 3]. Van Hove predicted[1] that one or more localized rapidity bumps of higher local multiplicity would be observed in an event. However, no evidence of this type was ever found experimentally at the AGS, SPS or RHIC.

The Hanbury-Brown and Twiss (HBT) observations and analyses at RHIC[4, 5] have shown that for central Au + Au at $\sqrt{s_{NN}} = 200$ GeV the average final state source size radius at low p_t was approximately 6 fm, but reduced rapidly with increasing p_t to an average of ~ 2 fm for p_t greater than 0.8 GeV/c.

In our earlier bubble model paper we assumed[3] localized ~ 2 fm sources on the surface of the final state fireball. This size is consistent with the above HBT analyses for charged particles above 0.8 GeV/c in p_t. These sources are what we called bubble substructures(gluonic hot spots) and locally produce higher multiplicity than the surrounding fireball. The selection of particles with a momentum range $0.8 < p_t < 2.0$ GeV/c helps isolating the surface particles and thus the bubbles. Two-particle angular correlations techniques are a powerful method for searching for a substructure. In Ref.[3] we employed a two-particle two-dimension-

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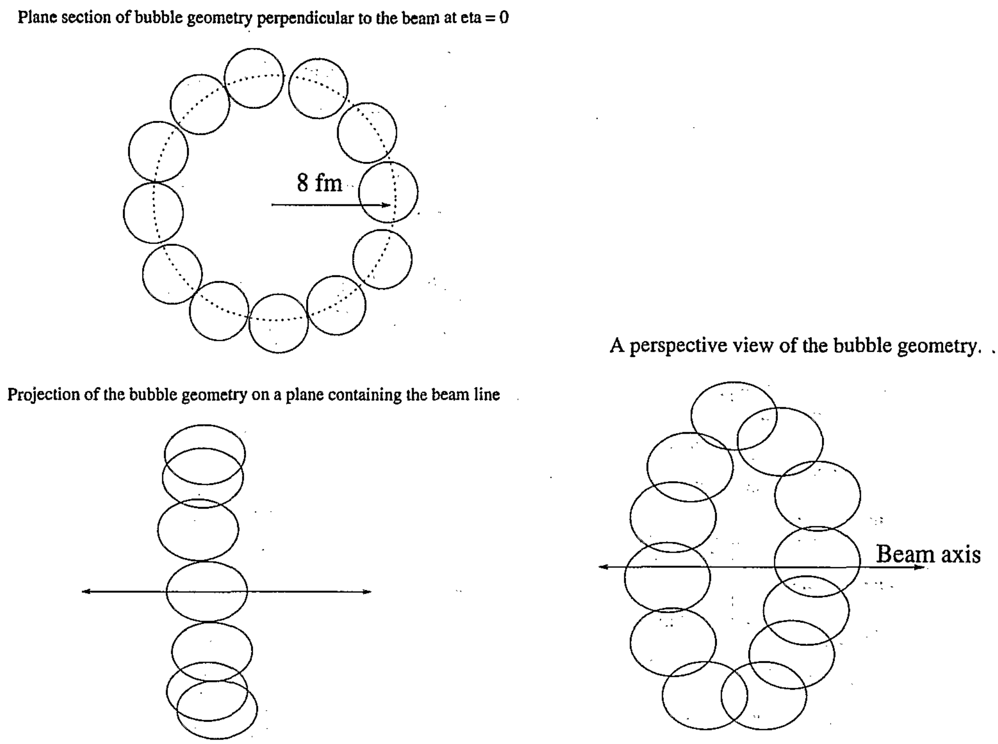

Figure 1: The bubble geometry is an 8 fm radius ring composed of twelve adjacent 2 fm radius spherical bubbles elongated along the beam direction by the Landau longitudinal expansion. The upper left figure is a plane section perpendicular to the beam at η =0. The lower left figure is a projection of the bubble geometry on a plane containing the beam line. The lower right figure is a perspective view of the bubble geometry.

angular difference $\Delta\phi\Delta\eta$ correlation. We assumed for mid-rapidity particles at freeze-out the correlations arise from a ring of adjoining 2 fm radius bubbles perpendicular to and centered on the beam wrapped around the outer surface of the blast wave driven fireball(see Figure 1). This bubble ring replaced the jets (sometimes call minijets) of HIJING[6] which were removed.

The correlation method we used has the property that all the bubbles in the ring, regardless of their individual positions, image on top of each other. Thus the bubble signal is enhanced by the number of bubbles in each event. In Ref.[3] we pointed out that the angular ϕ width of the observed correlation arising from phase space focusing of a $\sim$ 2 fm source is $\sim 30°$. Thus we have a consistent picture between HBT which shows phase space focusing size 2 fm and a blast wave boosted hot spot with its $\Delta\phi$ correlation width of $30°$[3]. The image correlation of the bubbles should lead to a positive correlation, because more particles are produced in the localized $\Delta\phi$ region than the average background. The $\Delta\eta$ correlation width depends on the longitudinal expansion of the bubble and is an input to the model[3, 7] to represent the Landau longitudinal expansion.

We consider for this article particles in the p_t range 0.8 to 2.0 GeV/c. The lower cut provides an enhancement of the individual 2 fm bubbles. The upper cut was used to avoid hard jet contamination. Our background particles come from HIJING beam jets, but were modified by elliptic flow which is a known component of $\Delta\phi$ correlations[3].

We made some predictions of the expected characteristics of future experimental results at $\sqrt{s_{NN}} = 130$ GeV. These predictions were in general consistent with the general characteristics later observed in the high precision experimental paper[8]. However our main focus in Ref.[3] was to determine the feasibility of, and motivate the analysis of high precision correlation data which would be detected in STAR. Then we would compare the model with the data analysis as a critical check of the model. The subsequent high precision STAR analysis is in the process of publication[8].

We recently submitted for journal publication[7] a refined bubble model which had partons as its starting point. Each localized bubble contains initially 3-4 partons which are almost entirely gluons forming a gluon hot spot. We greatly expanded the transverse momentum interval to 0.8 GeV/c $< p_t <$4.0 GeV/c. New experimental results demonstrate that quenching is so strong that our expansion of the p_t range is justified[9]. Quark-quark and antiquark-antiquark recombination effects become important in this intermediate p_t range. The bubble ring geometry is the same, it replaces the hard scatterings of the HIJING jets as before. However we further modified the bubble ring to conserve momentum in the transverse direction. Thus HIJING becomes merely our source of background particles since only the beam fragmentation remains(no correlations). Elliptic flow was added as before to the beam fragmentation particles since they should have knowledge of the reaction plane.

Ref.[8] had a p_t cut of 0.8 GeV/c$< p_t <$2.0 GeV/c consistent with our first multi-bubble model paper[3]. Therefore in making a comparison with new STAR data we have modified the Ref.[7] bubble model to have the above p_t range. The parton bubble model of Ref.[7] had already considered STAR data, in order to adjust parameters of the model[10]. Two major parameters are the number of partons(3-4) per bubble and their longitudinal momentum. The STAR analysis of Ref.[10] was earlier and consistent with the new analysis[8] for the Charge Independent(CI) $\Delta\phi$ correlation in two $\Delta\eta$ bins. The adjustment procedure, and many other details of the model are given and discussed in our extensive theoretical paper[7].

2 Unlike-sign and Like-sign charged pairs

There are two different basic types of pair correlations, unlike-sign charged pairs, and like-sign charged pairs. Both experiment and theory contains signals and background correlations in these two pair types. The separation of signal and background is model dependent, thus we will compare the entire experimentally observed correlation in STAR with the entire correlation generated by the parton bubble model.

Figure 2: left side shows a two dimensional(2-D) perspective plot of the total correlation(including background) for the unlike-sign charged pairs predicted by the parton bubble model. The right side shows the two dimensional (2-D) total correlation(including back-

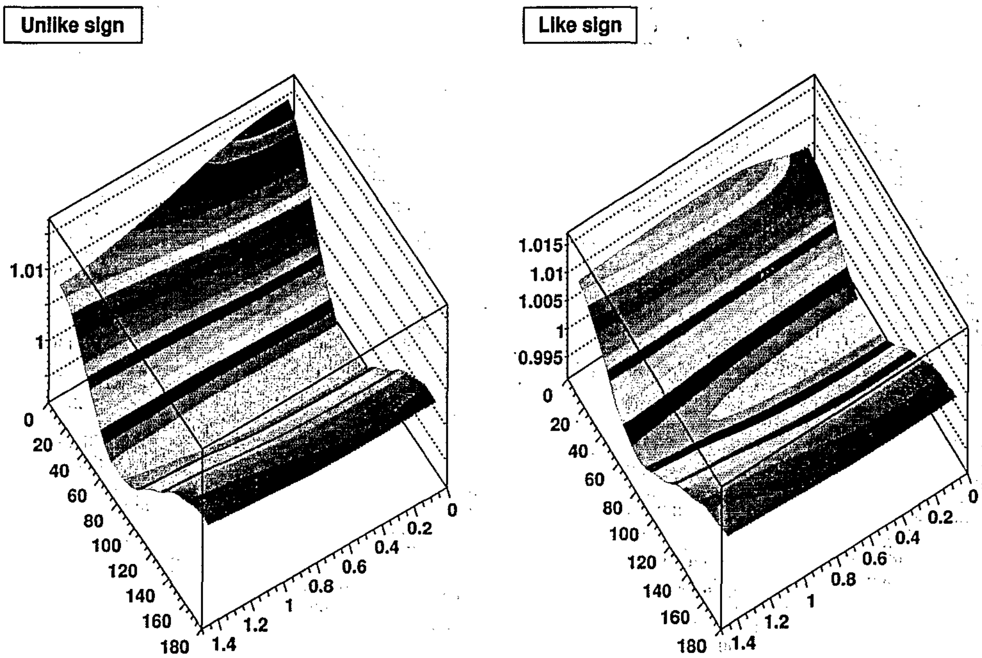

Figure 2: The left side shows a two dimensional(2-D) perspective plot of the total correlation(including background) for the unlike-sign charged pairs predicted by the parton bubble model. The right side shows the two dimensional (2-D) total correlation(including background) for the like-sign charged pairs for the parton bubble model.

ground) for the like-sign charged pairs for the parton bubble model.

Figure 3: left side shows the two dimensional(2-D) total correlation for the unlike-sign charged pairs determined in the STAR experiment. The right side shows the two dimensional(2-D) total correlation for the like-sign charged pairs determined in the STAR experiment. When comparing Figure 2 with Figure 3 note the scale on the right side of Figure 3 is somewhat enlarged compared to all other plots in Figure 2 and Figure 3.

The parton bubble model predictions are in reasonable agreement with the experimental data. A quantitative comparison will be made for the important physically interpretable Charge Independent(CI) and Charge Dependent(CD) total correlations in section III and IV respectively.

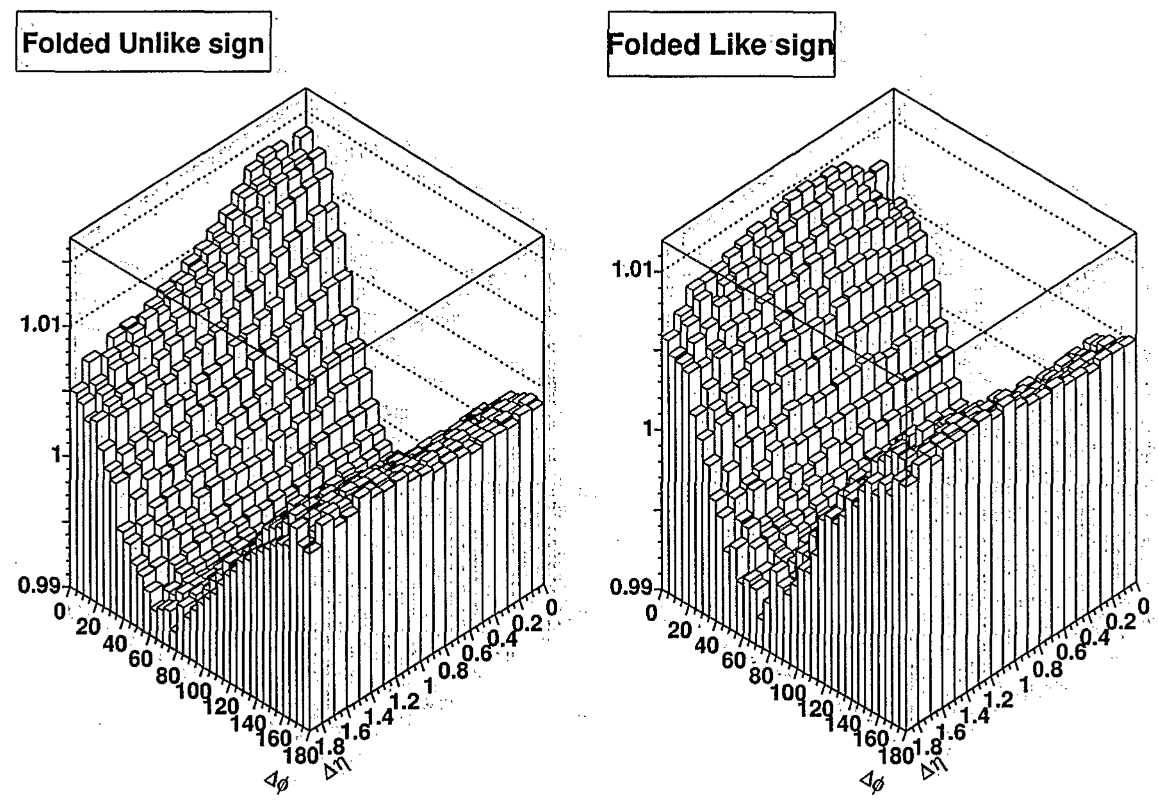

Figure 3: The left side shows the two dimensional(2-D) total correlation for the unlike-sign charged pairs determined in the STAR experiment. The right side shows the two dimensional(2-D) total correlation for the like-sign charged pairs determined in the STAR experiment. When comparing Figure 2 with Figure 3 note the scale on the right side of Figure 3 is somewhat enlarged compared to all other plots in Figure 2 and Figure 3.

3 Charge Independent Correlation(CI)

The Charge Independent(CI) correlation is defined as: CI = unlike-sign charge pairs correlation + like-sign charge pairs correlation. The CI is the most important correlation since it displays the average structure of the correlated emitting sources. As stated previously we need to compare the total experimental CI with the total parton bubble model CI. The analytic formulae for the experimental unlike-sign and like-sign charge pairs correlation are given in the STAR paper[8]. We generated two million 0-10% centrality events in order to compare with the CI correlation of STAR. In order to make a quantitative comparison we divide the 2-D CI up into 5 $\Delta\eta$ bins shown in Figures 4-8. In each $\Delta\eta$ bin we show the $\Delta\phi$ correlation for the CI as a function of $\Delta\phi$. The STAR Au + Au central trigger analysis results from the formulae are shown as a solid line. The parton bubble model predictions are shown by the circular points which are large enough to include the statistical errors from the 2 million events. The agreement is very good. The difference between the STAR experiment CI and the parton bubble model predictions for them in the five $\Delta\eta$ bins considered are smaller than approximately 0.1%. This is 10% of the observed correlation. The average differences are smaller, namely, 4% for 4 of the $\Delta\eta$ bins and 5% for the smallest $\Delta\eta$ bin. Thus we have successfully explained the observed CI correlation in this high precision experimental analysis in a reasonably quantitative manner with the parton bubble model.

4 Charge Dependent Correlation(CD)

The Charge Dependent(CD) correlation is defined as: CD = unlike-sign charge pairs correlation - like-sign charge pairs correlation. The subtraction of the like-sign charge pairs removes those pairs of unlike-sign particles that do not come from the same space time region. Thus the CD is a measure of the correlation of the unlike-sign pairs which are emitted from the same space-time region. We are assuming in the model that the emission of particles almost entirely occurs from the bubbles on the surface of the fireball after freeze-out when there is no further interaction between particles. The bubbles are mainly made up of gluons and are almost neutral in charge[3, 7].

Figure 9: shows a 2-D perspective plot of the CD predicted by the parton bubble model. It displays the two dimensional correlation between unlike-sign charge pairs from the same space-time region emitted from the surface of the fireball at freeze-out.

Figure 10: is the data plot in fig 6b from the STAR experimental paper[8] which is labeled as CD signal data. In the CD correlation the experimental backgrounds cancel almost entirely in the subtraction so that the entire CD is the same as the CD signal. In the parton bubble model they definitely cancel so the entire CD = the CD signal.

To quantitatively evaluate the agreement between the experimental CD and the parton bubble model CD, we make use of the relationship of the CD to the net charge fluctuation suppression. The net charge fluctuation suppression is directly related to an integral over the CD. We make a comparison of this suppression between the parton bubble model and the

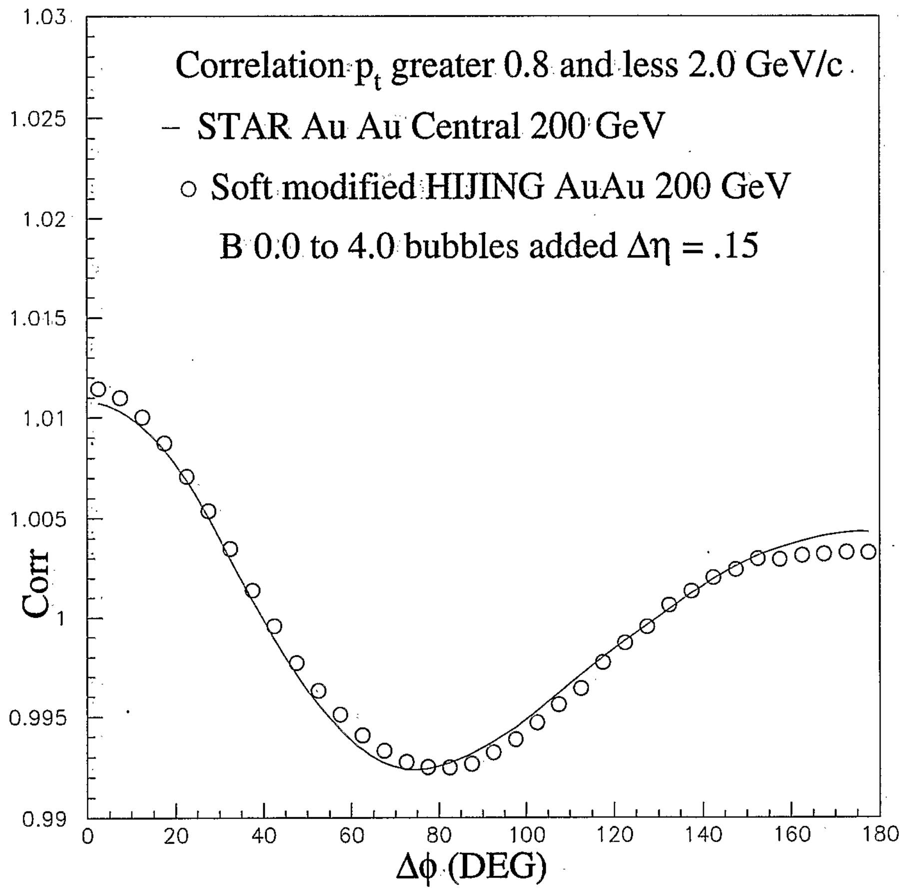

Figure 4: The $\Delta\phi$ charged particle pair correlation(o) for soft modified HIJING plus bubbles, which is the bubble model, compared to ref.[8] data(-) for $\Delta\eta$ 0.15(0.0< $\Delta\eta$ <0.3). The 0 -10% centrality in HIJING corresponds to impact parameter (b) range 0.0 to 4.0fm. The agreement is very good.

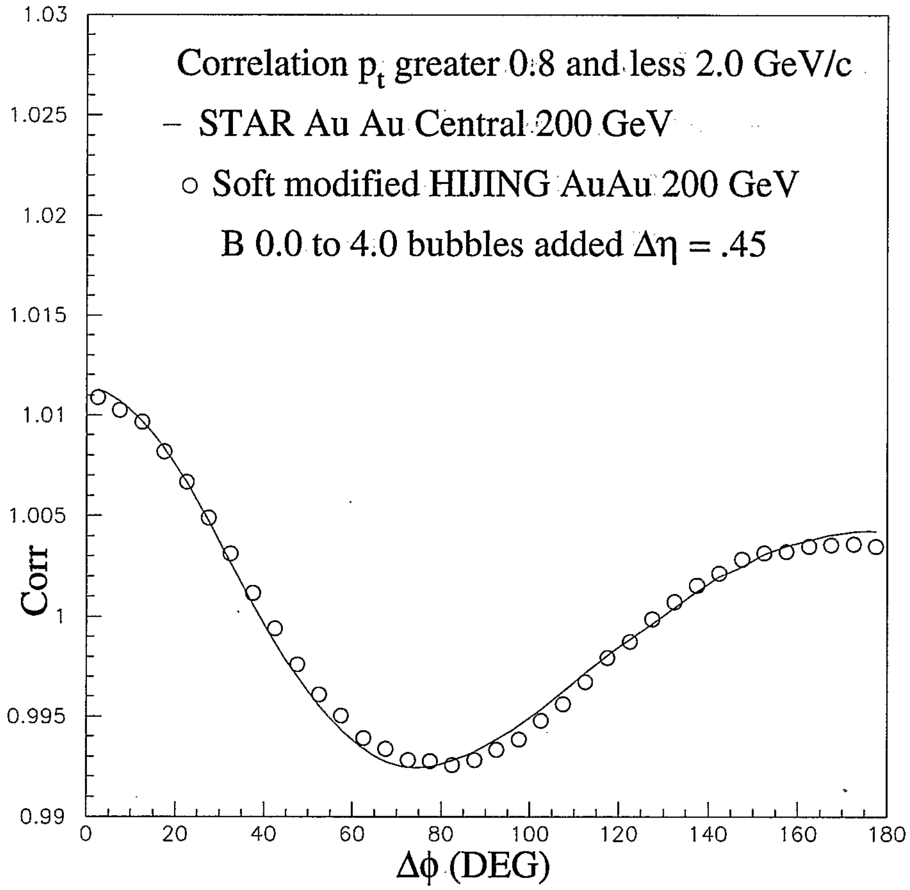

Figure 5: The $\Delta\phi$ charged particle pair correlation(o) for soft modified HIJING plus bubbles, which is the bubble model, compared to ref.[8] data(-) for $\Delta\eta$ 0.45(0.3< $\Delta\eta$ <0.6). The 0 -10% centrality in HIJING corresponds to impact parameter (b) range 0.0 to 4.0fm. The agreement is very good.

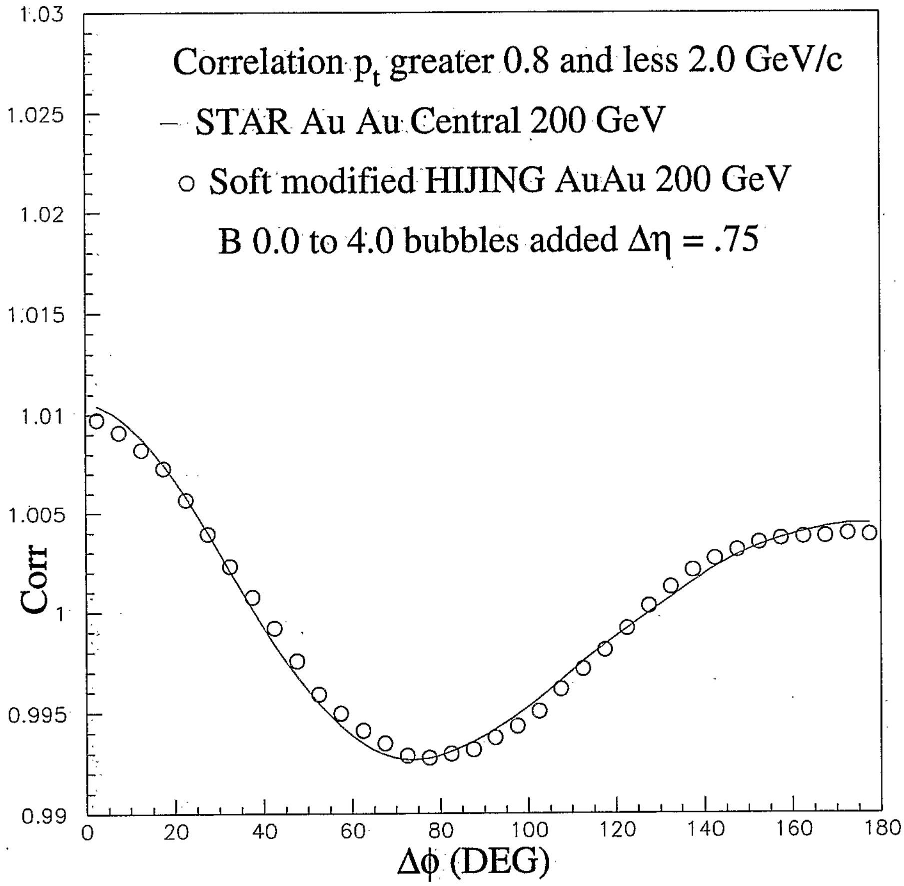

Figure 6: The $\Delta\phi$ charged particle pair correlation(o) for soft modified HIJING plus bubbles, which is the bubble model, compared to ref.[8] data(-) for $\Delta\eta$ 0.75($0.6 < \Delta\eta < 0.9$). The 0 -10% centrality in HIJING corresponds to impact parameter (b) range 0.0 to 4.0fm. The agreement is very good.

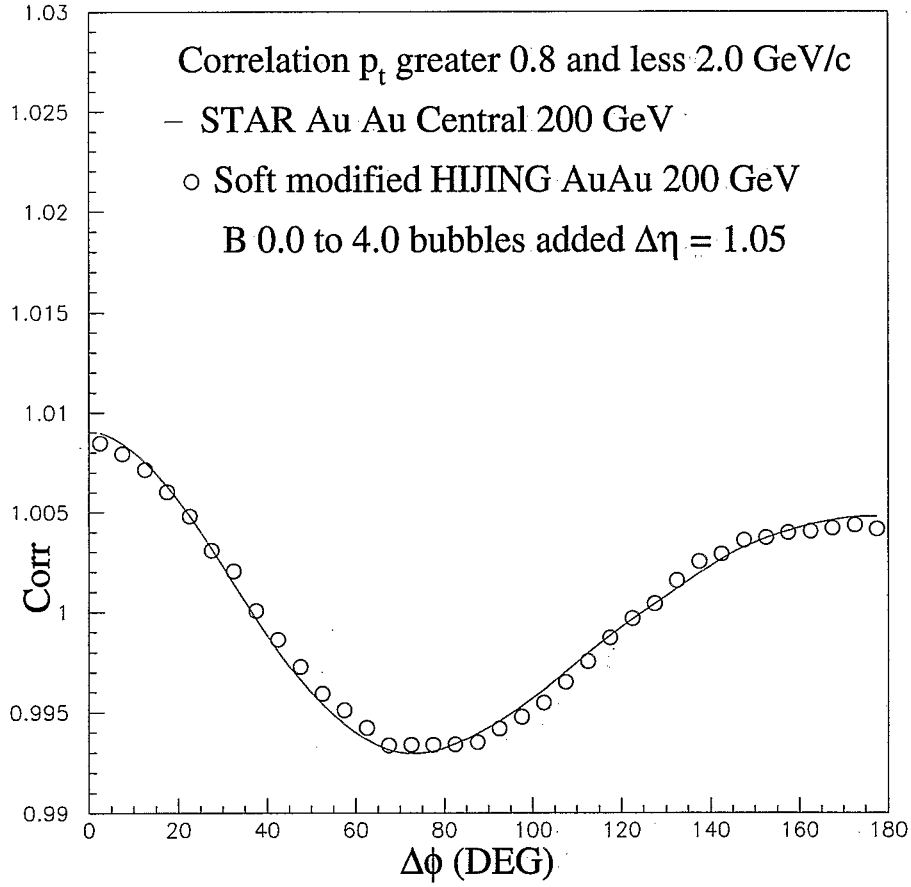

Figure 7: The $\Delta\phi$ charged particle pair correlation(o) for soft modified HIJING plus bubbles, which is the bubble model, compared to ref.[8] data(-) for $\Delta\eta$ 1.05(0.9< $\Delta\eta$ <1.2). The 0 -10% centrality in HIJING corresponds to impact parameter (b) range 0.0 to 4.0fm. The agreement is very good.

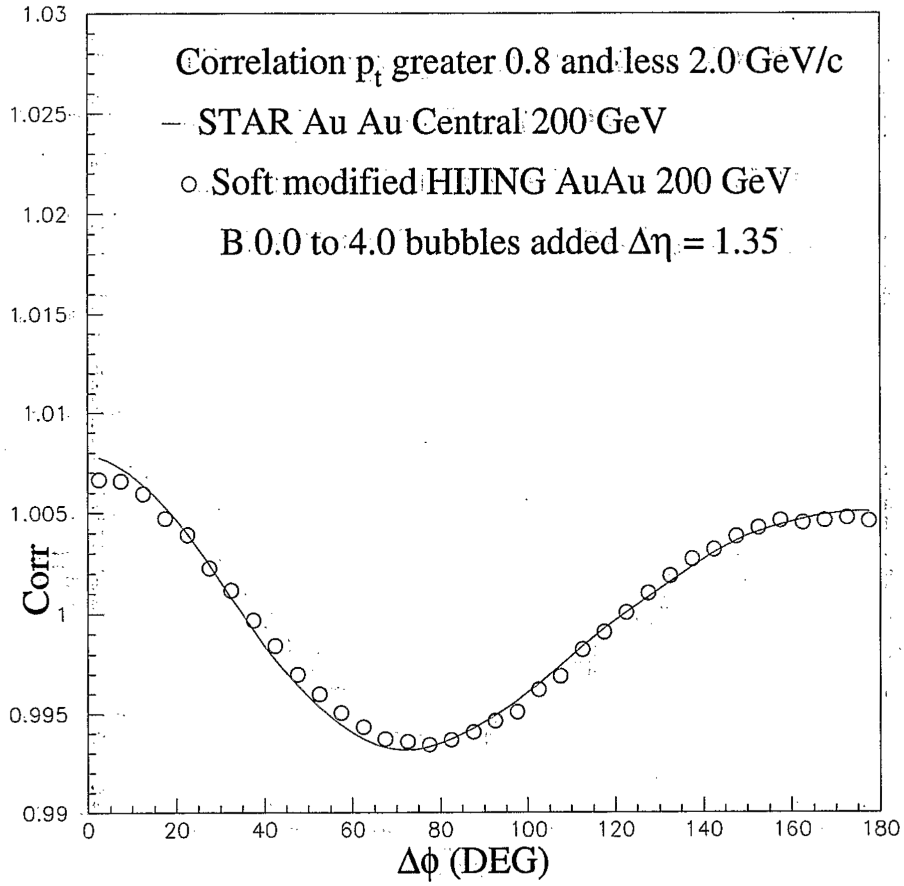

Figure 8: The $\Delta\phi$ charged particle pair correlation(o) for soft modified HIJING plus bubbles, which is the bubble model, compared to ref.[8] data(-) for $\Delta\eta$ 1.35(1.2< $\Delta\eta$ <1.5). The 0 -10% centrality in HIJING corresponds to impact parameter (b) range 0.0 to 4.0fm. The agreement is very good.

experimentally observed suppression. The net charge fluctuation suppression is the observed percentage reduction in the RMS width of the distribution of the event by event difference of the number of positive tracks minus the negative tracks, compared to the RMS width of a random distribution.

We performed a charge difference analysis for the parton bubble model particles within the same cuts as the STAR experimental paper[8] which were $0.8 < p_t < 2.0$ GeV/c and $|\eta < 0.75$, and used the same method described there. For each parton bubble model event we determined the difference of the positive particles minus the negative particles in our cuts. There was for the sum of these a net mean positive charge of 4.70 ± 0.01. The width of the charge difference distribution was given by the RMS as 10.82 ± 0.01. To determine the net charge fluctuation suppression we need to compare this width with the width of the same set of particles with a random charge assigned. Then this distribution would have no net charge fluctuation suppression.

However we must arrange a slight bias toward a positive charge particle so that we will end up with the same net mean positive charge. We now cycle through the events assigning a random charge to each particle with a slight bias toward being positive, we obtain a mean of 4.70 ± 0.01 and width(RMS) of 11.47 ± 0.01. The percentage difference in the width which measures the net charge fluctuation suppression is $5.7\% \pm 0.2\%$.

The results of the experimental STAR analysis[8] were that the net charge fluctuation suppression value was $6.0\% \pm 0.2\%$, and the mean net charge was 4.68 ± 0.01. The parton bubble model results agree within the errors with the STAR experimental analysis results. Thus the CD for both agree quantitatively.

5 Summary and Conclusions

We have modified the p_t and η cuts in the parton bubble model[7] in order correspond to the cuts in the analyses of the high precision STAR experiment[8] for central Au + Au $\Delta\phi$ $\Delta\eta$ correlations at $\sqrt{s_{NN}} = 200$ GeV. We have then shown that the bubble model predictions agree reasonably quantitatively with the experimental analyses of the Charge Independent(CI) and Charge Dependent(CD) correlations.

The Charge Independent(CI) correlation displays the average structure of the correlated emitting sources. The differences between the STAR experiment CI correlation and the parton bubble model CI predictions for the five $\Delta\eta$ bins compared are smaller than $\sim 0.1\%$. This is 10% of the observed correlation. The average differences are even smaller, namely, 4% for 4 of the $\Delta\eta$ bins and 5% for first and smallest $\Delta\eta$ bin.

The quantitative comparison of the Charge Dependent(CD) correlation of the STAR experiment and the parton bubble model was made by comparing the net fluctuation suppression which is related to the integral of the CD. The net charge fluctuation suppression was $6.0\% \pm 0.2\%$ for the STAR experiment and $5.7\% \pm 0.2\%$ for the parton bubble model. The net mean positive charge for the experiment was 4.68 ± 0.01 and 4.70 ± 0.01 for the parton bubble model. These values agree within errors.

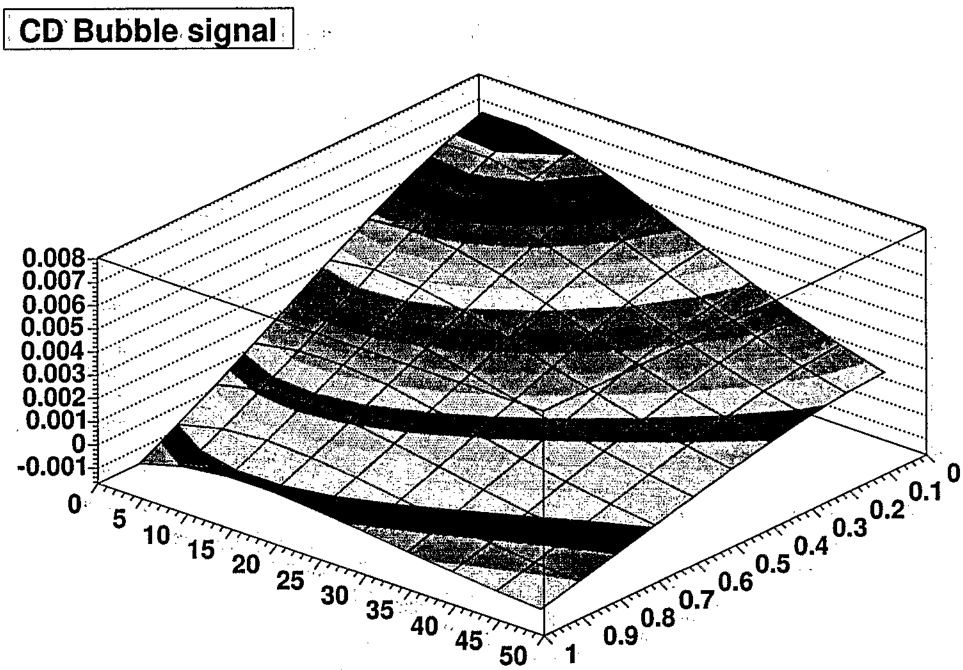

Figure 9: A two dimensional(2-D) perspective plot of the Charge Dependent(CD) correlation predicted by the parton bubble model. It is the same as the CD signal since the background cancels when one subtract the like-sign charge pairs correlation from the unlike-sign charge pairs correlation. This correlation displays the unlike-sign charged pairs correlation from the same space-time region emitted from the surface of the fireball at freeze-out.

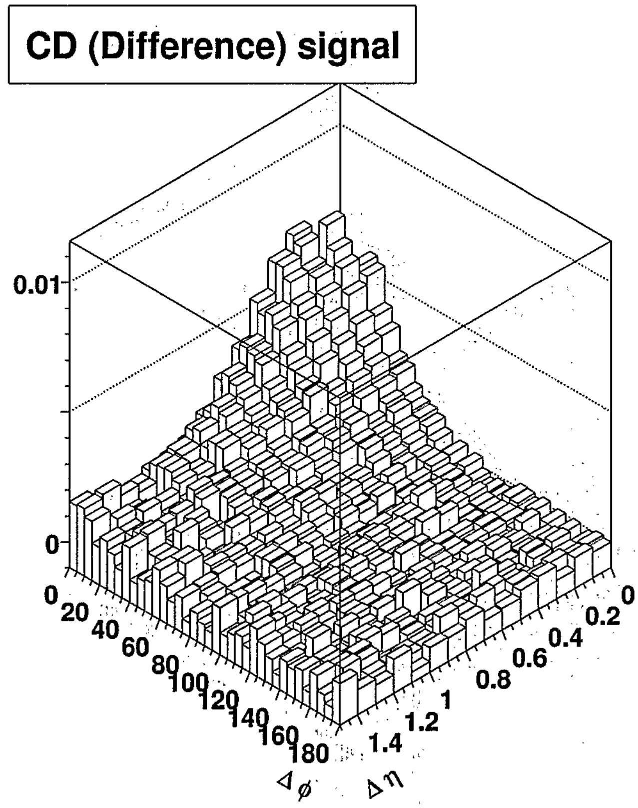

Figure 10: The Charge Dependent(CD) signal determined by the STAR experimental analysis. It is observed to be the same as the entire CD correlation. In section IV it is shown via a quantitative analysis that in Figure 10 the experiment agrees in the integral with Figure 9 the parton bubble model.

We observed very close agreements with a high precision correlation analysis which was performed under conditions closely to those incorporated in the parton bubble model. This implies substantial evidence that the basic properties of the parton bubble model are likely the dominant characteristics present in the data.

These observed characteristics of the parton bubble model which lead to the good agreement of the CI and CD correlation, implies that the individual sources of correlated particles are likely localized gluonic hot spots which reside on the surface of the fireball.

6 Acknowledgment

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